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COMPARATIVE STUDY OF THE MUON-CATALYZED FUSION IN D-T AND D-^{3}He SYSTEMS

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I RESEARCH PROPOSAL

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ABSTRACT

In the last five years there has been a revival of interest in muon (μ)-catalyzed fusion reactions as a source of energy production. The measurements and calculations reported[1] deal mainly with the D-D and D-T systems which result in an energy release of 3.5 and 17.6 MeV respectively. The secondary neutrons produced in these reactions carry the larger fraction of the energy, 2.3 MeV in the D-D and 14.1 MeV in the D-T reactions. The study of the muon-catalyzed fusion of the light-ion system D-^{3}He is of interest since the absence of radioactive tritium makes this reaction a source of "Clean Energy Fuel". In this reaction, $d + {}^3He \longrightarrow p + {}^4He + 18.3$ MeV, a 14.7 MeV proton is emitted instead of the 14.1 neutron from the D-T system. Although these two mirror systems (isospin flip), D-T and D-^{3}He, are equivalent in regard to the nuclear interaction (they differ only in the Coulomb interaction), it would be also of interest to study the differences among the mesomolecular processes that will give rise to the μ-catalyzed fusion.

The objective of this proposal is to carry out a comparative study of the muon-catalyzed reactions, D-T and D-^{3}He by measuring the number of neutrons/μ and protons/μ under equivalent experimental conditions. The comparison will be made as function of the T or ^{3}He concentration in the systems, their densities and temperatures. Since some measurements[2-4] of the D-T system are already available, the present study will concentrate on the D-^{3}He system and in that region of the parameter space (concentration-density-temperature) not covered by the existent neutron work, mainly, mixtures at very high pressures and temperatures.

The experimental results will be compared with calculations of the neutron[5,6] and proton yields resulting from the mesomolecular processes taking place between the muon and the deuterium-tritium and deuterium-helium mixtures.

INTRODUCTION

The "Cold Fusion" process in which a catalyzing agent, such as a negative meson, induces the fusion reaction was first discussed by Frank[7] (1947) and Sakharov[8] (1948) and experimentally observed[9] in 1957. The interest in this process as a potential energy source has been revived by recent experiments[3,4]. Close to 100 fusions reactions have been measured for for each meson present in deuterium tritium mixtures at high density (~ liquid hydrogen density, LHD). Independent of the viability of cold fusion as an economical choice for fusion power [10,11], the muon catalyzed fusion process is of interest because of the atomic, molecular and nuclear processes that are involved in its interpretation.

A consistent body of experimental results and further theoretical work are needed for an understanding of the muon-catalyzed fusion process with respect to the mesomolecular formation[5,6] of the μDT, μD^3He molecules. How does the strong nuclear interaction in the D-T, D-^{3}He reactions affect[12] the molecular and atomic processes? How do the hyperfine components of the mesomolecular formation determine[13] the fusion rates? How does the resonant theory of molecular formation hold at high temperatures? To answer these questions the appropriate measurements need to be performed. μ catalysis has been shown[3,4] to depend on the density, temperature, and tritium concentration of the D-T mixture. This dependence needs to be systematically explored at higher pressures and temperatures. It is also of interest to extend this study to the D^3He mixtures, for which calculations on the mesomolecular formation have only recently become available[14].

The scope of the present proposal is to carry out measurements of the catalyzed fusion reaction for the D-T and the D-^{3}He systems by observing the emission of neutrons and protons, respectively. These measurements, in collaboration with K. Crowe (UC, Berkeley), and C. Petitjean (Swiss Institute for Nuclear Research, SIN, Switzerland) will look first into the neutron emission as a function of temperature and pressure of the D-T mixture. Some overlap with early experiments is desirable in order to test the reproducibility of the earlier results[3,4]. However, the interest of the proposed measurements is principally into the regime of high pressures ($\sim$ 1000 atm) and temperatures ($1\text{-}5\times10^3$ K). Both Jones *et al.*[3] and Breunlich *et al.*[4] have shown an increasing, but different temperature dependence of the neutron production rate (per muon stopped in the D-T mixture) in the 30 to 900 K interval. The interpretation of the results differ among these groups. Observed[4] hyperfine components of the μtd formation rate seem to require a revision of the predicted[15] neutron rates and its dependence on temperature.

Measurements at higher temperatures ($1\text{-}5\times10^3$ K) would test the resonance theory of the μtd molecule formation. Would the system be "thrown out of resonance" at these temperatures and the catalysis process be stopped? Would there be a continuous increase of the neutron rates as a result of new resonances being excited? Similar questions could be answered by measurements at high pressures. Does the neutron rate increase progresively with higher densities of the D-T mixture or is a plateau reached at a given pressure? Does the catalysis stop at very high densities due to an increasing number of α particles and increasing μ^4He sticking?

Proton measurements will follow after replacing the D-T mixture by D-^{3}He gas for the same experimental conditions of ^{3}He concentration, pressure and temperature. The comparison of the rates of neutron and proton emission per incident μ meson from the catalyzed D-T and D-^{3}He reactions would give interesting information into the mesomolecular processes between these two reactions. Would protons be observed in coincidence with the meson? In other words, is there a bound state for the μ^3HeD molecular system as in the D-T mixture? How different are the lifetimes of the μt and μ^3He atoms? Would the sticking coefficient of the μ to the ^{3}He be of the same order as the value obtained[16] for the α particle? Are the mesomolecular processes affected by the isospin flip ($n \longrightarrow p$) term in the strong interaction Hamiltonian for the D + T and D + ^{3}He nuclear reactions?

The proposed measurements would shed light on the possibility of using the D-^{3}He reaction as a source of catalyzed fusion. This is in itself a very attractive choice since it eliminates the need for tritium with its intrinsic health hazard problems. Furthermore, the comparative study of the neutron/proton emission would stimulate further theoretical work into the μTD system and needed calculations for the μ^3HeD. Some insight also could be gained on the effect of nuclear processes from two equivalent (only isospin flip) nuclear reactions on the catalyzed fusion process.

MEASUREMENTS

The measurements will be done at SIN using the μE4 beam and the experimental setup would be essentially the same used in previous measurements[4,13]. A schematic view of the double wall target cell (a safety requirement for tritium handling) and detector system is shown in Fig. 1. For the high pressure D-T measurements (10^3 at), a new cell will be designed. It will be built at LLNL using their expertise in high pressure targets and tritium handling. For the D-^{3}He mixture a simplified design (no need for a double wall container) would be used. Details of the gas pumping, storage and purification systems have been given elsewhere[13].

A beam telescope consisting of three plastic scintillators, M_1, M_2, M_3, defines the muon stops in the cell while the electrons from muon decay are detected by plastic scintillators E_1, E_2 and E_3 (see Fig. 1). This arrangement[4,13] of detectors and their electronics would be common to both the neutron and proton measurements.

Neutron Measurements

The nominal 14 MeV neutrons will be detected using standard[17] time-of-flight (TOF) techniques. The detectors, NE213 liquid scintillators (30cm diam x 20cm) will be positioned one at each side of the gas cell. They will be viewed with 13 cm diam 8854RCA photomultipliers optically coupled to the detectors through a light pipe. Pulse-shape discrimination will be used to suppress the background. Neutron background from interactions of the muons or the 14 MeV fusion neutrons with the walls of the cell will be identified by TOF. The detector efficiency for 14 MeV neutrons will be obtained by a Monte Carlo calculation using the code[18] NEFF4. Good agreement has been found[19] with this code for the measured and calculated efficiencies for NE213 and Stilbene detectors. Multiple scattering corrections will need to be made to account for the thick walls of the cell and high gas pressure.

Proton Measurements

The proton measurements will be made first for the same range of pressures (1-3 x 10^3 atm) and temperatures (10-900 K) as the neutron measurements (See summary of the existing measurements in Pg. 55 of Ref. 1). Only at very low pressures (a few atmospheres) would it be possible to have a thin window, so that the energy lost by the 14.6 MeV proton in the mixture and through the window will not be larger than a few hundred keV. This would allow the proton detector to be outside the gas cell. Silicon surface barrier detectors (ΔE-E telescope), 150-200 microns total thickness, would be used to detect the protons. Because of the smaller diameter of the Si detectors, the solid angle subtended by the proton telescope could be about an order of magnitude smaller than that of the neutron detector if installed at the same position. However, by bringing the detector close to the window and because of the larger efficiency of the Si detectors (100% versus 3-4% for the neutron detector) an overall gain in detection efficiency is obtained.

For measurements at very high pressures the Si detectors would be installed inside the gas cell (pasivated Si detectors with an epitaxial layer over the p-n junction) because of the large fraction of energy lost by the proton in the D-^{3}He mixture. i.e. for a mixture at 1000 atm pressure the total energy lost by the 14.6 MeV proton in reaching the walls of a 5cm diameter cell is around 9 MeV. Furthermore, at these high pressures the thickness of the window will stop altogether the already low-energy emerging protons.

To install the proton detectors inside the gas cell is a very practical approach that could be used over the entire range of pressures of the measurements. The only limitation would be as a result of the increasing leakage current of the Si detectors at higher temperatures. Under this arrangement, 450-500 K could be an upper limit for these measurements.

ANALYSIS OF THE RESULTS

The analysis of the data will be carried out at Berkeley. The Monte Carlo calculations of the neutron detector efficiency and of the neutron and proton transmision from the gas cell to the detectors will be done using the 7600 MFI computer. The nuclear cross sections for the $T(d,n)^4He$ and $^3He(d,p)^4He$ reactions in the eV region and their angular distributions would be obtained from an R-matrix analysis[20] of the mass-5 system.

The measured neutron emission rates, after being corrected for background contributions from neutrons originating in the cell walls, will be compared with calculations. The results will be compared with the predicted decay rates of the mesomolecular formation as obtained from previous analyses[4,13], in order to clarify the role of the hyperfine structure decay channels. Fig. 2 is illustrative of the model for the muon catalysis in the DT mixture as presently accepted[13].

A parallel analysis of the proton emission rates would be a test of the recent Russian calculations[14] and would give information as to the applicability of the model to the D^3He system. Calculations have been initiated[21,22] based on this proposal on the mesomolecular formation mechanism for the μ^3HeD molecule and the values for the sticking coeficients of the μ to the ^3He and ^4He atoms. It is expected that these calculations will be available at the time of completion of these measurements.

Note added in proof:

Although the term "mesomolecular" has been used throughout the text, according to its common usage in the literature, it is a poor choice[23] since the muon is not a meson.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig. 1 Schematic representation of the experimental arrangements for the D-T (Fig. 1a) and D-^{3}He (Fig. 1b) mixtures. M_1, M_2, M_3 muon beam defining detectors. E_1, E_2, E_3 muon's decay electron detectors. NE213 neutron detectors. P_1, P_2 proton detectors

Fig. 2 Model of the processes taken place when negative muons are stopped in a mixture of deuterium and tritium, including hyperfine transitions. (Taken from Ref. 4). c_d and c_t are the atomic concentrations of deuterium and tritium. The λ's correspond to the different rates of molecular formation. λ_{hf} denotes the hyperfine transition: $\lambda_{hf} = c_t\lambda_{tt\mu} \quad c_d\lambda_{dt\mu}$.
J is the total spin of the μt atom and w_s is the sticking coefficient of the muon to the ^{4}He.

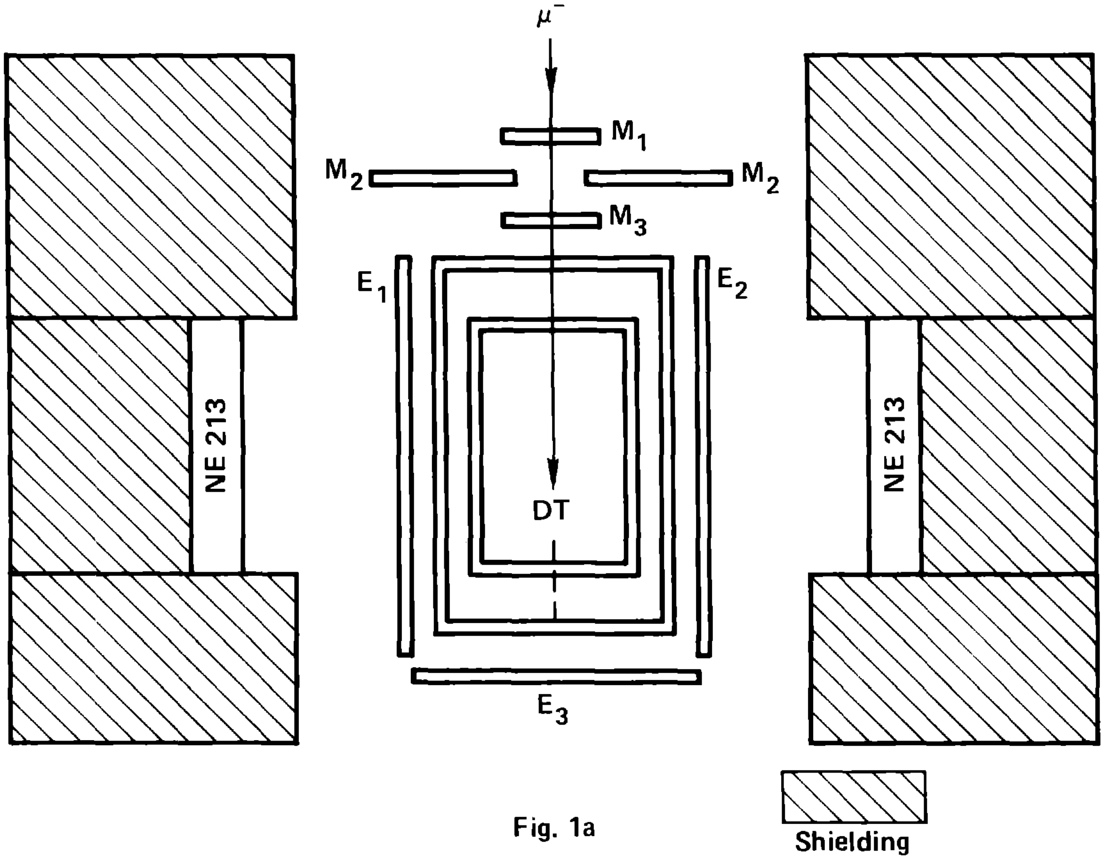
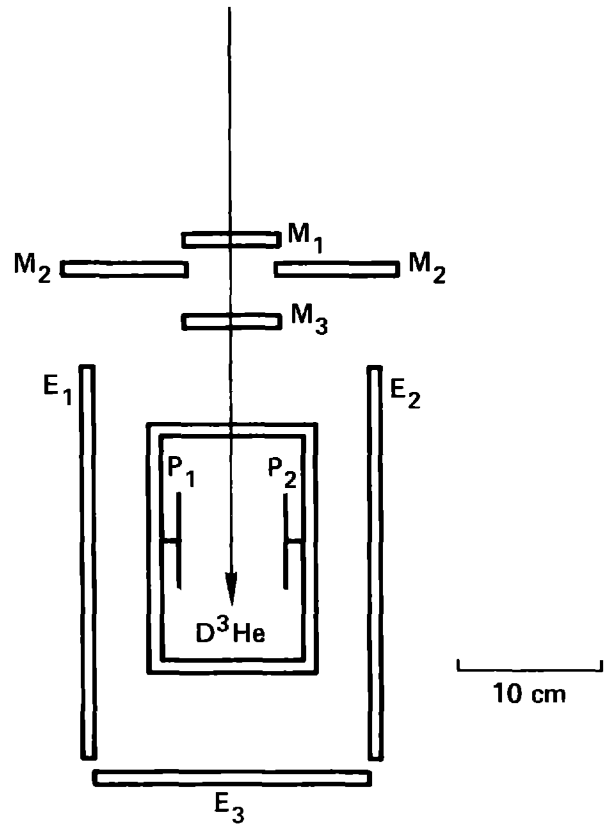

μ⁻
M1
M2
M2
M3
E1
E2
NE 213
NE 213
DT
E3
Shielding

Fig. 1a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M2
M2
M3
E1
E2
P1
P2
D3He
10 cm
E3

Fig. 1b

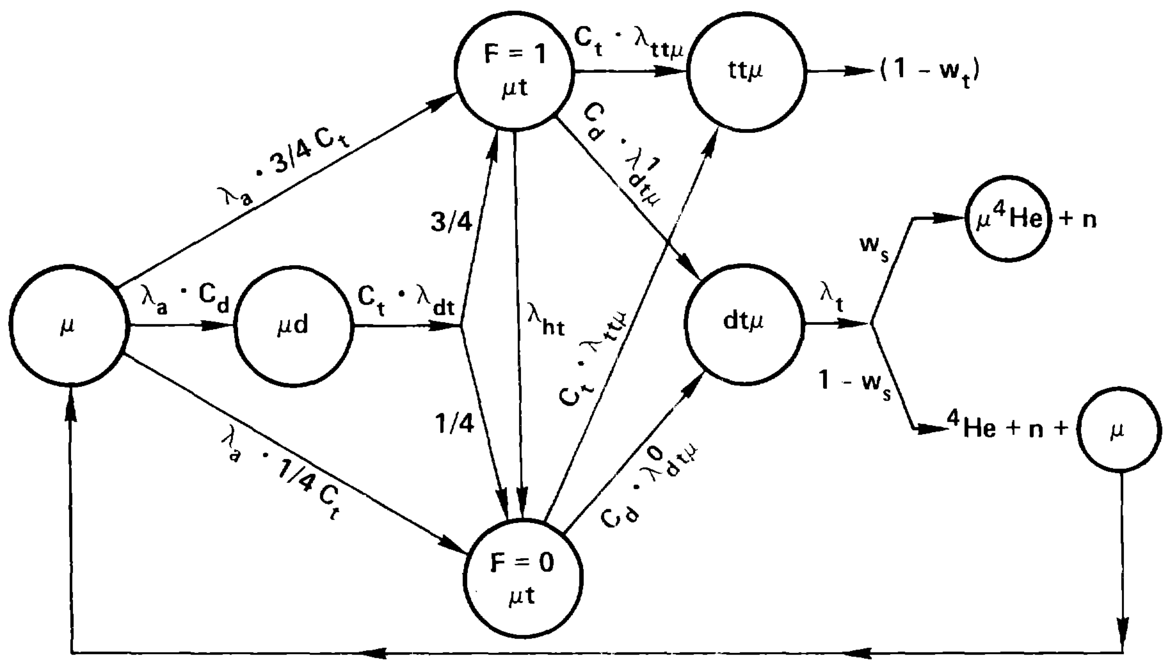

Fig. 2. The DT fusion cycle